

CURRENT CAPACITY DEGRADATION IN SUPERCONDUCTING CABLE STRANDS

L. F. Goodrich and S. L. Bray
National Bureau of Standards
Boulder, Colorado 80303

Abstract

The electromagnetic properties of NbTi strands extracted from Rutherford cables were studied to clarify the effect of mechanical deformation, caused by the cabling process, on the current capacity of the strands. Three different cables were studied, all of which are prototypes for the Superconducting Super Collider's dipole magnets. The extracted cable strands were instrumented to allow measurement of the voltage across several key regions of mechanical deformation as a function of current and the orientation of the applied magnetic field. The resulting data are presented in terms of the strand's voltage profile as well as its critical current in order to more thoroughly characterize the conductor's electromagnetic properties. The cable strands show very localized reductions in current capacity that are well correlated with the regions of high mechanical deformation. For example, at a particular field orientation, the voltage across a portion of the strand that is only 3% of the total strand length contributes 92% of the total strand voltage. Two applied magnetic field orientations, parallel and perpendicular to the cable's width, have pronounced effects on the electrical properties of the strand. Both of these magnetic field orientations will arise in applications.

Introduction

The measurements presented here are a continuation of earlier studies¹ of NbTi cable strands extracted from Rutherford cables (cables provided by the Lawrence Berkeley Laboratory). These are prototype cables for high energy physics applications. Specifically, they were designed for use in the outer windings of the Superconducting Super Collider's (SSC) dipole magnets. The main emphasis of these studies is the effect of mechanical deformation, during manufacture, on the cable's current capacity. In addition to the bending deformation required to achieve the cable's twist pitch, the cables are compacted into a keystone shape. These mechanical deformations result in a very localized degradation in the electrical properties of the cable strands. The deformation of the cable strands results in a periodic geometry with the various segments of the strands defined by the degree and type of deformation. The desired product of this work is information that will lead to methods for reducing the current-capacity degradation associated with the manufacture of superconducting cables.

For all the measurements, the orientation of the applied magnetic field was perpendicular to the cable's longitudinal axis. The angle of the applied field about this axis was set at either the 0° (parallel to the cable width) or 90° (perpendicular) orientation. The reasons for emphasizing these field directions are twofold. First, there is a pronounced effect on the strand's electrical properties in these orientations and, second, both of these field orientations arise in a dipole magnet. The experimental details of this work will be reported in a future publication.²

The mechanical deformation of the cable strands during the cabling process results in localized variations in the conductor's current capacity. The

sources of this variation fall into two categories, cross-sectional area differences and angular effects. The cross-sectional variation of the superconducting filaments is due to necking and serrated yielding of the NbTi filaments. Under the second category, angular effects, the orientation of the applied magnetic field with respect to the conductor's longitudinal axis (pitch angle effect) and its mechanically deformed cross section (aspect ratio effect³) vary along the strand.

Three different cables, manufactured with different virgin wire (source wire for the cable strands) and cabling techniques, were studied. These data allow comparisons among the cables. The strand critical current (strand I_C) is defined as the current at which the sum of the voltages from each of the strand segments divided by the sum of the segment lengths is equal to a selected electric field criterion. The strand I_C is presented for both magnetic field orientations, 0° and 90°. This information is useful in examining the cumulative effect of variations in spatial orientation and aspect ratio of different strand segments at different field angles. The concept of a strand I_C is also useful for comparing the strand's I_C with the I_C of the virgin wire from which the cable was manufactured. These comparisons indicate the amount of I_C degradation introduced by the cabling process. In order to assess the relative contribution to the total voltage of different strand segments, the voltage distribution along the conductor's length, at both magnetic field angles, is also presented.

Three different cables, denoted as W, X, and Y, were studied. Cable W was re-rolled through a turkshead (for resizing) after it had been cabled. The re-rolled cable is a worst-case situation that was studied to more clearly identify the degradation features. Cable X is similar to W; however, it was not subjected to as much mechanical deformation and is a more typical example of late 1985 to early 1986 prototype outer cables. Cable Y (1987) is an evolution of cable X where the cabling techniques were refined in an attempt to reduce current-capacity degradation.

Results

The conductors measured in this study represent an evolution in the cable fabrication process aimed at reducing its detrimental effect on the critical-current density (J_C) of the finished cable in comparison to that of the virgin wire.⁴ An evolution has also occurred in the design and processing of the virgin wire.⁵ This evolution can be characterized by a decrease in filament size aimed at reducing ac losses while attempting to maintain the J_C . Initially, the increased wire drawing that was used to reduce the filament size of wire X in comparison with wire W resulted in a lower J_C . Later, improved manufacturing processes that were used for wire Y resulted in a substantial restoration of the J_C of the virgin wire.

Strand Critical Current

I_C measurements were made on the virgin wires from which each respective cable was manufactured. Three pairs of voltage taps, with each pair spanning about 10 mm, were connected to the specimens. This allowed

for a check of I_c homogeneity with position. I_c measurements were also made as a function of the applied magnetic field angle. This allowed for a test of I_c homogeneity with respect to field angle. The average I_c of the virgin wire was used to determine the relative degradation of each cable. The typical I_c variation among voltage taps was $\pm 0.3\%$ at 5 T and $\pm 0.5\%$ at 8 T for all of the virgin wire samples. For samples X and Y, the I_c variation of a given tap with respect to field angle (0° to 360°) was measured to be about $\pm 0.6\%$ at 5 T.

Figures 1 and 2 show comparisons between the J_c of the extracted cable strands (strand J_c) and the virgin wires from which they were constructed. Figure 1 shows this comparison for each of the three conductors for applied magnetic field angles of 0° and 90° at 5 T. There is a consistent increase in the J_c at 0° from cable W to cable Y although the virgin wire's J_c decreased between wires W and X. Since cable W is a worst-case situation with respect to the cabling operation, the higher J_c for strand X is due to the reduced mechanical deformation of the strand. Cable Y shows a greater mechanical degradation of its J_c than cable X, but, again, it shows an increased strand J_c due to its high virgin wire J_c . For cable strand X, the mechanical degradation of the J_c was somewhat higher at 90° than at 0° and, consequently, there was a decrease in the J_c of strand X as compared with the J_c of strand W. This increased degradation at 90° was not present in strand Y and strand Y showed an increased J_c in comparison with its two predecessors.

The 8 T plot, Fig. 2, shows an increase in the strand's J_c between W and Y but there is a decrease between W and X. Comparison between the 5 and 8 T J_c degradation for all of the strands shows a reduced sensitivity to mechanical deformation at the higher magnetic field for all the strands. The virgin wire W, which has larger diameter filaments, had a higher relative J_c at 8 T than do wires X and Y. This lower sensitivity of wire W to magnetic field results in a higher strand J_c for W than for X.

Differential Voltage Profile

Figures 3 and 4 show the electrical properties of the cable strand as a function of the position along its length. At the top of each plot, located outside the axes, is an outline of the cable strand's geometry positioned so as to correlate with the horizontal or position axis. The cable outline is labeled to indicate the position of the thin edge, the face, and the thick edge relative to the horizontal axis. The differential voltage across the various strand segments is plotted as a function of position. The plateaus, or peak levels, in the curves represent the voltage across the indicated strand segments at the indicated strand I_c . The lines connecting the data are only a visual aid and they are not intended as an interpolation between the data points. The current levels for each of the different samples is not the same in these plots (current levels for each of the strands is given in the figure captions); however, the overall voltage level is the same for each of the samples. In other words, the data in these plots represents the same strand I_c criterion ($0.1 \mu\text{V}/\text{cm}$) for each of the samples.

The plots show that there is a considerable variation in the lengths of the various strand segments. Herein lies the significance of these plots, which show the relative contribution of the separate strand segments to the overall voltage.

For the samples and conditions existing in these measurements, the total voltage seems to determine the

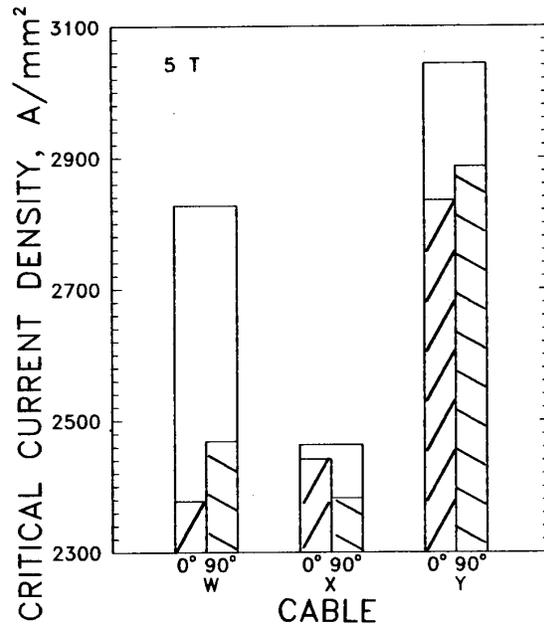


Figure 1. Critical current density of cable strands and their respective virgin wires for 0° and 90° at 5 T. The virgin wire J_c is represented by the continuous line segment spanning 0° to 90° for each cable. The strand J_c values at 0° and 90° are represented by the shaded bars for each cable.

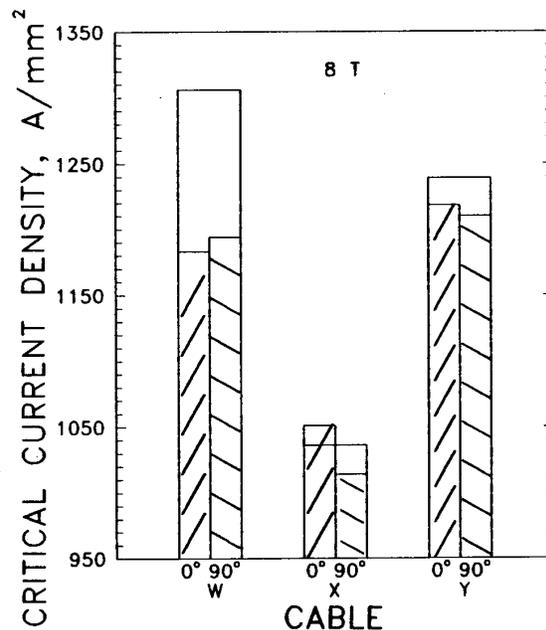


Figure 2. Critical current density of cable strands and their respective virgin wires for 0° and 90° at 8 T. The virgin wire J_c is represented by the continuous line segment spanning 0° to 90° for each cable. The strand J_c values at 0° and 90° are represented by the shaded bars.

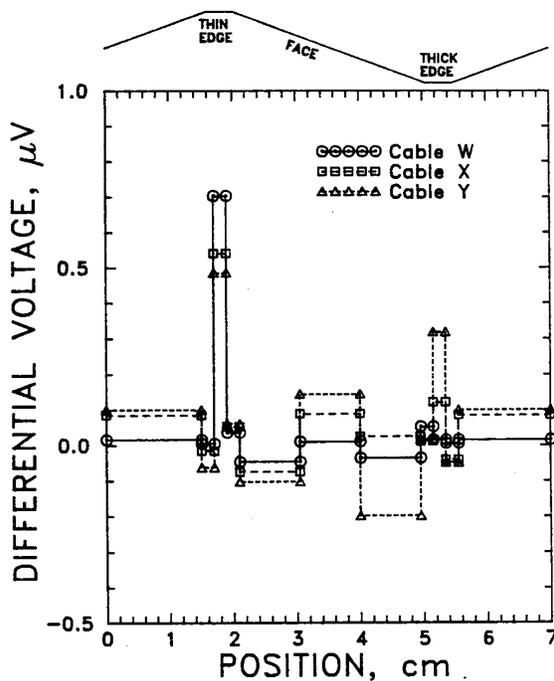


Figure 3. Differential voltage profiles at 5 T and an applied magnetic field angle of 0° for cables W, X, and Y at currents of 285 A, 307 A, and 339 A respectively.

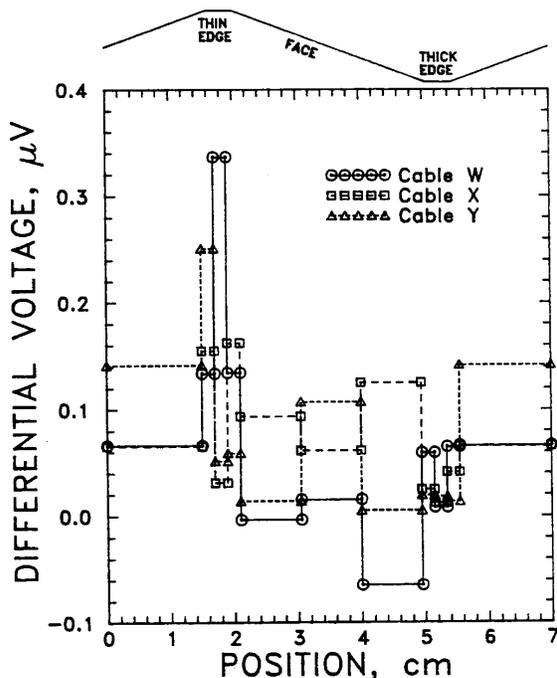


Figure 4. Differential voltage profiles at 5 T and an applied magnetic field angle of 90° for cables W, X, and Y at currents of 296 A, 300 A, and 345 A respectively.

current capacity of the conductor. This is evidenced by a close agreement between the measured strand critical currents and the maximum achieved currents (quench currents). For a sample that has poor longitudinal thermal conductivity, the short edge segments might act as weak links, limiting the current capacity to a value below that required to reach the strand I_c criterion. For all cables and the 0° orientation, the majority of the voltage is concentrated at the edges of the cable with the central portions being dominant. At 90° , the voltage concentration increases at the corners of the edges in comparison with the centers.

The negative voltages shown in the plots are projection voltages^{6,7} associated with current redistribution among the filaments. The strongest evidence of intrinsic (not associated with the location of the current contact) transverse currents within the strand is a region of negative voltage bounded by regions of large positive voltages. The curve for cable Y is the best example of this structure. This type of structure is present in the center of these plots. This indicates that the current redistribution is caused by the longitudinal variation in the relative current carrying capacity of the filaments rather than being caused by current injection at the current contact. Thus, voltages associated with this type of redistribution will occur periodically along the entire length of the cable strand.

Although the negative voltages are the most obvious indication of current redistribution, there are other indicators. These indicators have the same general character as the negative voltages with the exception of polarity. The positive current transfer voltages are evident when observing a series of differential voltage plots in which the sample current is increasing. There are portions of the differential voltage profile that rise abruptly, like a flux flow voltage, and then level off with increasing current until the actual flux flow region is reached. These transitory positive voltages, like the negative voltages, are indicative of intrinsic current redistribution within the cable strand.

Discussion

The main objective of this work is to determine the current capacity of several different cable strands with the ultimate goal being an increased understanding of the sources and degree of current capacity degradation in these conductors. Typically, the I_c of a conductor is an accepted practical measure of its current capacity. However, for these particular conductors, there are some difficulties in relating I_c to the actual current capacity of the cable strands. Owing to the electrical inhomogeneity of the strands caused by the cabling operation, there is a large variation in the I_c along the strand's length. The problem is determining what current level in this fairly broad range of critical currents best reflects the strand's practical current capacity.

One approach is to assume a weak link situation where the strand segment that has the lowest I_c determines the overall current capacity of the strand. A comparison between the actual quench currents (the maximum observed current prior to thermal runaway) and the weak link I_c shows that the current capacity of the strand is significantly higher than the weak link I_c . This enhanced current capacity, above the weak link I_c , is due to the strand's relatively good stability.

At the other extreme, the current capacity of the strands could be assumed to be equal to the strand I_c . For the conductors tested here, this would not be a bad

assumption, as evidenced by the close agreement between the strand I_C and the quench currents. However, there are two problems associated with simply measuring the strand I_C and assuming this to be the strand's practical limit. First, the strand I_C gives no information about the voltage distribution along the strand's length and, consequently, it is not useful in understanding the sources of current degradation in the cable. Also, for conductors that are less stable than those tested here, the actual current limit might be close to the weak link I_C and, in this case, the strand I_C level could not be achieved.

Another factor associated with the I_C measurements for these cable strands is the presence of intrinsic current-transfer voltages that are caused by periodic current redistribution along the strand's length. This current transfer is apparently caused by the periodic mechanical deformation of the strand and, thus, it is not limited to the current contact area. Due to its intrinsic nature, these current transfer voltages play a role in determining the current capacity of the cable, not only in testing but in application as well. It is clear that I_C data alone are insufficient for characterizing these conductors. For this reason the differential voltage data were also presented.

Conclusions

Based on these measurements, some general conclusions can be stated regarding the electromagnetic character of these cables and its effect on their current capacities. Also, the measurements have implications regarding short sample testing of these cables.

The mechanical deformation of the cable strands associated with the cabling process can lead to very localized reductions in their current capacity. The widest spread in local current capacity occurs with the applied magnetic field parallel to the cable's width. Despite large local variations in the cable strand's current capacity, the quench current and the strand I_C do not vary much with the angle of the applied magnetic field. The deformation geometry of the cable is such that the interaction between the applied magnetic field and a strand segment's aspect ratio or its pitch angle have the same tendency. In other words, a field angle that is detrimental (beneficial) to a strand segment's current capacity due to its aspect ratio is also detrimental (beneficial) due to its pitch angle. However, the various strand segments have different critical orientations such that the detrimental and beneficial effects of the field angle on the various segments tend to cancel one another over the total length of the strand. For these particular conductors, the relevant I_C criteria may be a spatial average (the strand I_C) because the degradation in current capacity is concentrated over short regions of the cable strand and local temperature rises are limited by strong end cooling. Any compromise in sample stability may lower the I_C to that of the weak link segment of the cable strand.

These results have two implications for short-sample I_C testing of cables. First, the data indicate that both magnetic field orientations, parallel to the cable's width and perpendicular to its width, need to be tested to determine the limiting orientation for the I_C . The limiting magnetic-field orientation can be parallel or perpendicular to the cable's width and the limiting orientation is not known beforehand. Second, a large difference in current capacity degradation can exist between the thick and thin cable edges; thus, changing the direction of the test current (for each field orientation) can affect the measured I_C . This is due to a self field effect where the location of the

peak magnetic field depends on the current direction. Thus, the peak field location should be part of the data recorded for short sample measurements of these conductors. Consequently, these more detailed cable measurements should be made periodically as part of the cable development process.

The wire from which these cables are made has evolved to the point where they have a high virgin current capacity and a relatively high tolerance to mechanical deformation. Considering the amount of mechanical deformation of the strands caused by the cabling process, the resulting degradation in current capacity is surprisingly low. In the case of the latest outer winding cable, sample Y, the maximum observed degradation in its strand I_C was only 6.8%.

Acknowledgements

The authors extend their thanks to T. C. Stauffer for sample preparation, to A. N. Srivastava for data plotting; and to R. M. Scanlan and J. M. Royet (Lawrence Berkeley Laboratory) for samples and discussions.

This work was supported by the Department of Energy, Division of High Energy Physics.

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